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(54)   **A temperature measuring system and a sensor unit of such a temperature measuring system**

(57)   The invention relates to a temperature measuring system for the contactless determination of the object temperature (T_v) of at least a part of an object. The system is provided with a sensor unit (2) which is to be placed near the object and which comprises a first and second metal plate (4, 14 respectively). A temperature-sensitive sensor is disposed on each plate to produce first and second sensor signals (10, 18 respectively) which represent the temperature of the first plate (4) and second plate (14) respectively. The system also includes a control unit (12) which processes the first and second sensor signals (10, 18) in combination for determining the object temperature (T_v). Use is preferably made of a Kalman filter.
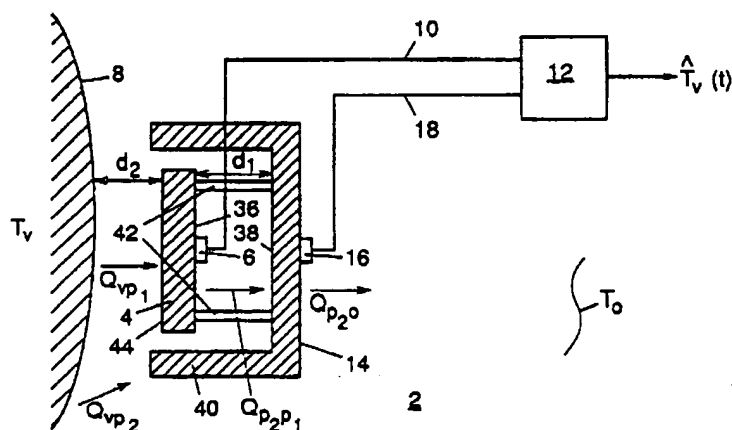
FIG. 5

EP 0 756 161 A1

Description

The invention relates to a temperature measuring system for the contactless determination of the object temperature (T_v) of at least a part of an object, provided with a sensor unit which is to be placed near the object and which comprises a first metal plate on which a first temperature-sensitive sensor is disposed to produce first sensor signals which represent the temperature (T_{p1}) of the first plate and a control unit which processes the first sensor signals for determining the object temperature (T_v). The invention also relates to a sensor unit for use in the temperature measuring system and an image reproduction machine provided with the temperature measuring system.

Temperature measuring systems of this kind are known per se and are used inter alia for determining the surface temperature of heated rotating rollers and heated endless belts in reproduction systems, such as copying machines and printers. In such cases the surface temperature is equivalent to the said object temperature. Here the temperature measuring system forms part of a measuring and control system for measuring and controlling the object temperature. One problem which occurs in these conditions is that the rotating roller or moving belt may be damaged if the sensor unit contacts the same to measure the object temperature. The rotating roller or moving belt might be scratched or otherwise affected. If the attempt is made to measure the object temperature without making contact with the object, the problem arises that the first plate of the sensor unit will generally assume a temperature differing from the object or part of the object. This is due inter alia to an unknown heat flow from the first plate to the surroundings. Consequently, the object temperature cannot be determined accurately. US patent 5 287 155 proposes measuring the temperature of the first plate at least once when the first plate makes contact with a stationary heated roller and comparing it with a measured temperature of the first plate when it is not in contact with the roller. From these measurements a differential temperature is determined which is then used as a correction value for the temperature measured when the first plate is not in contact with the roller. The disadvantage of this method, however, is that there is still a risk of damage to the roller when the first plate makes contact with the stationary roller. Even when the roll is not moving it may, for example, be dented by the first plate. Also, this known method is often not sufficiently accurate, because the correction value may unnoticeably fall off in the course of time, e.g. because of a change in the ambient conditions such as air humidity and ambient temperature. Also, a correction value determined when the roller is stationary will generally differ from a correction value applicable with the roller moving. The movement of the roller may, for example, cause air flows near the sensor unit, and these influence the ambient conditions and hence the accuracy of the temperature measuring system.

The object of the invention is to obviate the above disadvantages and is characterised in that the sensor unit is also provided with a second metal plate spaced from the first plate and having a second temperature-sensitive sensor disposed thereon to produce second sensor signals representing the temperature (T_{p2}) of the second plate, the control unit processing the first and second sensor signals in combination with one another to determine the object temperature (Tv).

Since, according to the invention, a second contactless temperature measurement is carried out by means of the second plate, new information is obtained regarding the object temperature, which information is generally at least partially independent of the information obtained by means of the first plate. This at least partial Independence is achieved by the fact that the second plate will occupy a different position with respect to the object compared with the first plate. In other words, the second plate is so positioned with respect to the first plate that if in respectively stable states ratios (To/T_v) between, on the one hand, an ambient temperature (T0) of the sensor unit and, on the other hand, the temperature (Tv) of the object differ from one another the associated ratios ((T_{p1}/T_{p2}) between, on the one hand, the temperature (T_{p1}) of the first plate and, on the other hand, the temperature (T_{p2}) of the second plate also differ from one another.

Consequently, on the basis of physical considerations, the object temperature can be determined very accurately in a completely contactless manner even if the ambient conditions change. If required, the ambient temperature can also be determined on the basis of the measured temperature of the first plate and the second plate respectively. This latter also implies that the influence of the ambient temperature on the determination of the object temperature can be eliminated.

The said independence and hence the accuracy of the temperature measuring system can further be boosted by so constructing the first plate and the second plate that they have different dimensions from one another.

According to a particular embodiment of the temperature measuring system according to the invention, the first and second plates each comprise an inner surface and an outer surface which are situated opposite one another, the inner surfaces of the first and second plates facing one another. The advantage of this is that the information concerning the object temperature obtained by means of the first plate will be largely independent of the information regarding the object temperature obtained by means of the second plate. Consequently, the measuring accuracy of the system will further increase.

Preferably, the second plate is further provided with upright side walls which extend from the inner surface of the second plate in the direction of the first plate, the first plate being situated within a space enclosed by the side walls of the second plate and the first plate being situated, in use, between the second plate and the object. Consequently, the heat flow from the first plate to the surroundings will at least approximately be equal to zero. A physical consequence

of this is that the information obtained by means of the first plate and the information obtained by means of the second plate are largely independent of one another, so that the measuring accuracy of the system will increase.

According to a very advantageous embodiment of the temperature measuring system, the control unit comprises a Kalman filter for determining the object temperature (T_v) on the basis of the first and second sensor signals. Use of the Kalman filter enables the object temperature to be so determined that it is possible to take into account all the relevant heat transfer coefficients between the object, the first plate, the second plate and the surroundings and in addition the thermal capacities of the first and second plates respectively.

More particularly, the Kalman filter is dimensioned on the basis of a model having at least three state variables which are respectively formed by the temperature (T_{p1}) of the first plate, the temperature (T_{p2}) of the second plate, the object temperature (T_v) and the ambient temperature T_o of the sensor unit, and by measured quantities formed by the temperature (T_{p1}) of the first plate and the temperature (T_{p2}) of the second plate.

The invention will now be explained with reference to the drawing wherein:

Fig. 1 shows a known temperature measuring system;
Fig. 2 is a first embodiment of a temperature measuring system according to the invention;
Fig. 3 is one possible embodiment of a Kalman filter of the temperature measuring system according to Figs. 2 or 5;
Fig. 4 is one possible embodiment of a control unit of the temperature measuring system according to Figs. 2 or 5;
Fig. 5 shows a second embodiment of a temperature measuring system according to the invention;
Fig. 6 shows the sensor unit of Fig. 5, and
Fig. 7 shows a model response to a stepwise change in the object temperature (T_v).

In Fig. 1, reference 1 denotes a temperature measuring system known per se. The temperature measuring system 1 comprises a temperature sensor unit 2 which in this example is formed by a metal plate 4 and a temperature-sensitive sensor 6 disposed on the metal plate 4. In this example, the metal plate is disposed near an object 8 whose temperature T_v is to be determined by the temperature measuring system 1.

The temperature-sensitive sensor 6 is disposed on the metal plate 4 to produce sensor signals representing the temperature T_p of the plate 4. These sensor signals are fed via a line 10 to the control unit 12 which further processes the sensor signals for determination of the object temperature T_v.

The system operates as follows. As shown in Fig. 1, it is assumed that the temperature to be measured of the object or part thereof is T_v. The ambient temperature of the sensor unit 2 is assumed to be T_o. It is also assumed that the metal plate is made of a material such that the plate will assume the same temperature throughout. The plate 4 is therefore made of a material which is a very good thermal conductor, e.g. copper or aluminium. The temperature of the plate is denoted by T_p. On the basis of the known first law of thermodynamics,

$$C_{Tp} \cdot \frac{dT_p}{dt} = Q_{vp} - Q_{p0} \tag{1}$$

Here C_{Tp} is equal to the thermal capacity of the plate 4, Q_{vp} is equal to the heat flow from the object 8 to the plate 4 and Q_{p0} is the heat flow from the plate 4 to the surroundings. It is also assumed that

$$Q_{vp} = G_{vp} (T_v - T_p) \tag{2}$$

$$Q_{p0} = G_{0p} (T_p - T_0) \tag{3}$$

where G_{vp} represents the thermal conductivity coefficient of the object 8 to the plate 4 and G_{0p} the thermal conductivity coefficient from the surroundings to the plate. It should be noted that formulae 2 and 3 are based on physical assumptions. In principle, other assumptions are possible, e.g. a non-linear relationship between heat flows on the one hand and temperatures on the other.

Substitution of formulae 2 and 3 and formula 1 gives:

$$C_{Tp} \cdot \frac{dT_p}{dt} = G_{vp}(T_v - T_p) + G_{0p}(T_0 - T_p). \tag{4}$$

Formula 4 is an equation with two unknowns, i.e. T_v and T_0. This means that the object temperature T_v cannot be solved directly. Only if it is assumed that the heat transfer coefficient G_{0p} is negligible a stable situation ($dT_p/dt = 0$) $T_v = T_p$ can be obtained. Generally, however, an assumption of this kind brings a fairly considerable error in the determination of T_v. If T_v is of the order of magnitude of 100°C, for example, while the ambient temperature T_0 is, for example,

40°C, the error in the determination of T_v, i.e. the difference between T_v and T_p, will be some degrees C. If the object 8 is, for example, a heated roller of a copying machine or a printer, while the temperature measuring system 1 forms part of a measuring and control circuit with which the temperature T_v of the roller 8 is set to a required value, an error of this kind is unacceptably large.

Fig. 2 shows a temperature measuring system 13 according to the invention, wherein components which correspond to components of Fig. 1 have the same reference number as Fig. 1. As will be apparent from Fig. 2, the sensor unit 2 is provided with a first metal plate 4 on which a first temperature-sensitive sensor 6 is disposed to produce first sensor signals which represent the temperature (T_{p1}) of the first plate 4. The sensor unit 2 is also provided with a second metal plate 14 spaced from the first plate 4 and having a second temperature-sensitive sensor 16 disposed thereon to produce second sensor signals representing the temperature (T_{p2}) of the second plate 14. The first and second sensor signals are respectively fed via a line 10 and a line 18 to a control unit 12 which processes these signals in combination in order to determine the object temperature (T_v).

On the basis of the law of conservation of energy, the following applies for the temperature T_{p1}:

$$C_{Tp1} \frac{dT_{p1}}{dt} = Q_{vp1} - Q_{p10} + Q_{p2p1}. \tag{5}$$

Here C_{Tp1} is the thermal capacity of the first plate, T_{p1} the temperature of the first plate, Q_{vp1} the heat flow from the object 8 to the first plate, Q_{p10} the heat flow from the first plate to the surroundings and Q_{p2p1} the heat flow from the second plate 14 to the first plate 4. Similarly, on the basis of the law of conservation of energy, the following applies for the second plate:

$$C_{Tp2} \frac{dT_{p2}}{dt} = Q_{vp2} - Q_{p20} + Q_{p2p1}. \tag{6}$$

Here, C_{Tp2} is the thermal capacity of the second plate 14, T_{p2} the temperature of the second plate, Q_{vp2} the heat flow from the object to the second plate, and Q_{p20} the heat flow from the second plate to the surroundings. Once again, as discussed in connection with Fig. 1, the following assumptions have been made:

$$Q_{vp1} = G_{vp1} (T_v - T_{p1}) \tag{7}$$

$$Q_{p10} = G_{0p1} (T_{p1} - T_0) \tag{8}$$

$$Q_{p2p1} = -G_{p1p2} (T_{p1} - T_{p2}) \tag{9}$$

$$Q_{vp2} = G_{vp2} (T_v - T_{p2}) \tag{10}$$

$$Q_{p20} = G_{0p2} (T_{p2} - T_0) \tag{11}$$

Substitution of formulae 7 to 11 in formulae 5 and 6 gives the following:

$$C_{p1} T_{p1} \frac{dT_{p1}}{dt} = G_{vp1}(T_v - T_{p1}) + G_{0p1}(T_0 - T_{p1}) + G_{p1p2}(T_{p2} - T_{p1}) \tag{12}$$

$$C_{p2} T_{p2} \frac{dT_{p2}}{dt} = G_{vp2}(T_v - T_{p2}) + G_{0p2}(T_0 - T_{p2}) + G_{p1p2}(T_{p1} - T_{p2}) \tag{13}$$

Formulae 12 and 13 represent the sensor model. Derivation of the sensor model is based on the assumption that the temperature of the first plate is the same throughout and that the temperature of the second plate is the same throughout. It has also been assumed that the thermal capacity of the first and second plates is many times greater than the thermal capacity of the air between the object, the first plate, and the second plate. Finally, it has been assumed that the first and second temperature-sensitive sensors respectively measure the temperature of the first and second plates accurately. The sensor model comprises two linear differential equations with two unknowns T_v and T_0. Generally, such comparisons can be solved if they are independent. Formulae 12 and 13 can be converted to the following in the static case:

$$(G_{vp1}+G_{0p1}+G_{p1p2})T_{p1}-G_{p1p2}T_{p2} = G_{vp1}T_v+G_{0p1}T_0 \tag{14}$$

$$(G_{vp2}+G_{0p2}+G_{p1p2})T_{p2}-G_{p1p2}T_{p1} = G_{vp2}T_v+G_{0p2}T_0 \tag{15}$$

5   Equations 14 and 15 form two linear equations with two unknowns T_v and T_0. The unknowns T_v and T_0 can be solved from these equations if the determinant of the matrix G is not equal to 0, where:

$$G = \begin{pmatrix} G_{vp1} & G_{0p1} \\ G_{vp2} & G_{0p2} \end{pmatrix} \tag{16}$$

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    On the basis of physical considerations, the determinant of the matrix G will generally not be equal to 0. The unknowns T_v and T_0 can be solved more accurately in proportion as the determinant of the matrix G is closer to the 15 number 1. The determinant is therefore an analog index of independence from the matrix.

    In Fig. 2 the first and second plates 4, 14 are disposed at different distances from the object. This means that the first and second plates will generally make different "observations" from one another. This implies that the equations 14 and 15 will not be dependent on one another. Also the fact that the second plate in this example has different dimensions from the first plate may contribute to the said equations being independent of one another.

20   Preferably, the control unit contains a Kalman filter for determining the object temperature T_v on the basis of the first and second sensor signals. As will be explained hereinafter, the Kalman filter can be so dimensioned as to generate a solution for the equations 12 and 13. This dimensioning can be carried out as follows: first of all, with regard to the filter design, it is assumed that the object temperature T_v and the ambient temperature T_0 do not change:

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$$\frac{dT_v}{dt} = 0 \tag{17}$$

$$\frac{dT_0}{dt} = 0 \tag{18}$$

30

    This means that the object temperature T_v and the ambient temperature T_0 can be interpreted as state variables of the sensor system defined by the formulae 12 and 13. If the object 8 is, for example, a heated roller or a heated endless moving belt of a copying machine or a printer, this assumption need not generally be true. The temperature variations of the surroundings and the object are then generally less than 20°C per minute, so that in that case too the equations 35 17 and 18 can be assumed as sufficiently valid. Apart from the temperature T_v and T_0, the temperatures T_{p1} and T_{p2} can also be interpreted as state variables of the sensor model. The equations 12 and 13 can then be rewritten as follows:

40

$$\dot{\bar{x}}_M(t) = A \; \bar{x}_M(t) \tag{19}$$

45

$$\bar{y}_M(t) = \begin{pmatrix} T_{p1} \\ T_{p2} \end{pmatrix} \tag{20}$$

50

$$\bar{y}_M(t) = C \, \bar{x}_M(t) \tag{21}$$

where

55

$$\bar{x}_M(t) = \begin{pmatrix} T_{p1} \\ T_{p2} \\ T_v \\ T_0 \end{pmatrix} \tag{22}$$

$$C = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} \tag{23}$$

and A = 4 x 4 system matrix. On the basis of the assumptions according to equations 17 and 18, the coefficients of the bottom two rows of the matrix A will be equal to zero. If it is also assumed that the heat flow from the first plate to the surroundings is equal to zero, then it is a simple matter to derive the following for the matrix A:

$$A = \begin{pmatrix} \dfrac{G_{vp1} + G_{p1p2}}{C_{p1}} & \dfrac{-G_{p1p2}}{C_{p1}} & \dfrac{-G_{vp1}}{C_{p1}} & 0 \\[2mm] \dfrac{-G_{p1p2}}{C_{p2}} & \dfrac{-G_{0p2} + G_{vp2} + G_{p1p2}}{C_{p2}} & \dfrac{-G_{vp2}}{C_{p2}} & \dfrac{+G_{0p2}}{C_{p2}} \\[2mm] 0 & 0 & 0 & 0 \\[2mm] 0 & 0 & 0 & 0 \end{pmatrix} \tag{24}$$

However, it is not essential to make the latter assumption. Generally, all the coefficients of the top row will accordingly not be equal to zero. The possibilities outlined hereinafter for determining the value of the coefficients of the matrix can be applied generally, even if the said assumption is not made.

The differences between the values $\bar{x}_M(t)$ and $\bar{y}_M(t)$ which form a solution of the model equations 19 - 22 and the actual values $\bar{x}(t)$ of the state variables and the assumed values $\bar{y}(t)$ of the initial variables are due to two reasons: model errors and measurement errors. The model errors can be discounted in an unknown term $\bar{w}(t)$ by requiring the actual state quantities $\bar{x}(t)$ satisfying the following:

$$\dot{\bar{x}}(t) = A\,\bar{x}(t) + \bar{w}(t) \tag{25}$$

The following applies for the model error $\bar{w}(t)$:

$$\bar{w}(t) = \begin{pmatrix} w_1(t) \\ w_2(t) \\ w_3(t) \\ w_4(t) \end{pmatrix} \tag{26}$$

where $w_1(t)$, $w_2(t)$, $w_3(t)$ and $w_4(t)$ respectively represent the error introduced by the fact that not all the physical assumptions made are completely correct in the model according to formula 19. In this connection mention is made of system noise (or interference).

The measurements errors are discounted in an unknown term $\bar{v}(t)$ by requiring the following:

$$\bar{Y}(t) = \begin{pmatrix} T_{p1} \\ T_{p2} \end{pmatrix} + \bar{v}(t) = C\,\bar{x}(t) + \bar{v}(t) \tag{27}$$

Here, $\bar{y}(t)$ represents the observed variables including the measuring error. Also,

$$\bar{v}(t) = \begin{pmatrix} v_1(t) \\ v_2(t) \end{pmatrix} \tag{28}$$

where $v_1(t)$ is the measuring error of the first temperature-sensitive sensor 6 and $v_2(t)$ the measuring error of the second temperature-sensor 16. In this connection, observation noise (measuring noise) is involved in the case of $\bar{v}(t)$.

The coefficients of the system matrix A are directly related to the heat transfer coefficients of the equations 12 and 13. In order to determine the coefficients of the system matrix A and hence also the said heat transfer coefficients, the temperature T_v of the object and the ambient temperature T_0 per unit of time can be followed once, e.g. by means of an infrared camera. At the same time, the temperatures T_{p1} of the first plate and T_{p2} of the second plate per unit of time can respectively be followed by means of the temperature-sensitive sensor 6 and the temperature-sensitive sensor 16.

This measurement results in exactly assumed measurements $\bar{x}_m(t) = \bar{x}(t)$ which can be expressed as follows:

$$\bar{x}_m(t) = \begin{pmatrix} T_{p1m} \\ T_{p2m} \\ T_{vm} \\ T_{0m} \end{pmatrix} \tag{29}$$

The coefficients of the matrix A can be determined by minimalising the following criterion for the value J:

$$J = E\left(|\bar{x}_m(t) - \bar{x}_M(t)|^2\right) = minimaal = E\left(\bar{w}^T(t)\bar{w}(t)\right) \tag{30}$$

where E is the notation known per se for an expected value and $\bar{x}_M(t)$ is the value following from the sensor model according to formula 19.

To determine the coefficients of the matrix A, use can be made of the assumptions according to formula 24. However, it is also possible to determine the coefficients of the matrix A in accordance with formula 30, but without any assumption for the coefficients of the system matrix A. On the basis of the assumptions according to equations 17 and 18, the coefficients of the bottom two rows of the matrix A will beforehand be selected as equal to zero. In the literature there are also other ways of determining the coefficients of the matrix A, e.g. by means of "extended" or "adaptive" filtering. The method outlined above in accordance with formula 30 is therefore only one possible method of determining these coefficients.

After the coefficients of the matrix A have been determined as described above, the Kalman filter of the control unit 12 can be dimensioned as follows. For this purpose, Fig. 3 is a diagram showing the Kalman filter known per se. The part I situated above the horizontal broken line corresponds to the actual system and the part II situated beneath the broken line corresponds to the Kalman filter 19.

In the diagram of Fig. 3,

$\bar{x}(t_0)$ represents the initial state of $\bar{x}(t)$ at time t_0;
$\hat{x}(t_0)$ represents the estimated initial state of x(t);
$\hat{x}(t)$ represents the estimated state of x(t);
$\dot{x}(t)$ represents the fluctuation of x(t);
$\hat{\dot{x}}(t)$ represents the estimated fluctuation of x(t);
$\hat{y}(t)$ represents the estimated y(t); and
K represents the 2 x 4 amplification matrix.

The following parameters should also be dimensioned in the Kalman filter according to Fig. 3: the estimated initial state $\hat{x}(t_0)$ and the coefficients of the amplification matrix K. An initial estimate of T_v and T_0 can be obtained, for example, by solving the equations 12 and 13 for the static situation. As an initial estimate for T_{p1} and T_{p2}, the measurements at t = 0 are an obvious choice. From this the following applies as an initial estimate for T_v and T_0:

$$\begin{pmatrix} T_0 \\ T_v \end{pmatrix}_{t=t_0} = G^{-1} \begin{pmatrix} (G_{vp1}+G_{0p1}+G_{p1p2})T_{p1}-G_{p1p2} & T_{p2} \\ (G_{vp2}+G_{0p2}+G_{p1p2})T_{p2}-G_{p1p2} & T_{p1} \end{pmatrix}_{t=t_0} \tag{31}$$

With this the estimated initial state $\hat{x}(t_0)$ is also known.

The choice of the filter parameters, i.e. the coefficients of the matrix K, is to some extent arbitrary. The Kalman filter theory provides a method of arriving at a choice for the matrix K on the basis of known assumed statistical properties of $\bar{w}(t)$ and $\bar{v}(t)$; i.e. a normal (Gaussian) probability density distribution with known variations $E(\bar{w}(t)\bar{w}(t)^T)$ and $E(\bar{v}(t)\bar{v}(t)^T)$. Optimum values of these coefficients, which are accompanied by advantages to be explained in detail hereinafter, can accordingly be estimated by minimalising the following criterion J':

$$J' = E\left(|\bar{x}_m(t) - \hat{\bar{x}}(t)|^2\right) = minimaal \tag{32}$$

Here, $\bar{x}_m(t)$ can be measured once with exactly assumed sensors as discussed hereinbefore. The said minimalisation can be carried out in manner known per se by means of commercial computer programs. All the filter parameters are now determined and the control unit will give a reliable value $\hat{y}$. The latter can also be regarded as follows. From the configuration of the Kalman filter according to Fig. 3 the following applies:

$$\dot{\hat{\bar{x}}}(t) = A\hat{\bar{x}}(t) + K(\bar{y}(t) - \hat{\bar{y}}(t)) \tag{33}$$

Also:

$$\hat{\bar{y}}(t) = C\hat{\bar{x}}(t) \tag{34}$$

so that the substitution of equation 34 in equation 33 teaches that

$$\dot{\hat{\bar{x}}}(t) = (A-KC)\hat{\bar{x}}(t) + K\bar{y}(t) \tag{35}$$

If formula 35 is then deducted from formula 25, $\bar{y}(t)$ being substituted by means of formula 27, then the following applies:

$$\dot{\bar{e}}(t) = (A-KC)\bar{e}(t) + \bar{w}(t) - K\bar{v}(t) \tag{36}$$

where

$$e(t) = x(t) - \hat{x}(t) \tag{37}$$

It is apparent from formula 36 that the enlargement of the matrix K causes the error e(t) to converge rapidly towards 0. Even if the initial state is selected in reverse form, the error will finally converge towards zero. On the other hand, an enlargement of K also results in a stronger reaction to the measuring error $\bar{v}(t)$. This means that the above-described optimal choice of K comprises a compromise which is dependent on the relationship between the measuring noise and the system noise. In the literature this choice is described as a Kalman (Bucy) filter.

The way in which the Kalman filter according to Fig. 3 (part II beneath the broken line) is implemented in the control unit 12 is illustrated with reference to Fig. 4. Here, parts which correspond to one another in Figs. 2, 3 and 4 have been given the same reference number. Here the temperature-sensitive sensors 6 and 16 are both embodied as NTC resis-

tors. The temperature-sensitive sensor 6 is connected in series with a resistor 20 known per se. Similarly, the temperature-sensitive sensor 16 is connected in series with a resistor 22 known per se. Also, both the series-connected temperature-sensitive sensor 6 and the resistor 20, and also the series-connected temperature-sensitive sensor 16 and resistor 22 are connected in parallel with a common DC supply 24. The DC voltage at the junction 26 between the temperature-sensitive sensor 6 and the resistor 20 is thus an index of the measured temperature $T_{p1} + v_1(t)$ of the first plate 4. Similarly, the voltage at the junction 28 between the second temperature-sensitive sensor 16 and the resistor 22 is an index of the measured temperature $T_{p2} + v_2(t)$ of the second plate 14. The value thus obtained for $\bar{y}(t)$ is fed to the Kalman filter 19. The Kalman filter 19 generates the output signal $\hat{x}(t)$, which is fed to a selection unit 34 via line 32. Selection unit 34 selects the component $\hat{T}_v(t)$ from the signal $\hat{x}(t)$ for further processing.

Figs. 5 and 6 show a preferred embodiment of a sensor unit according to the invention. The sensor unit 2 again consists of a first plate 4 and a second plate 14. Here the first and second plates each comprise an inner surface 36, 38 facing one another. The second plate 14 is also provided with side walls 40, which extend from the inner surface 38 of the second plate 14 towards the first plate 4. These side walls have a length such that the first plate is situated within a space enclosed by the side walls 40 of the second plate 14. The first and second metal plates in this example are interconnected by plastic connecting parts 42. The latter have the property that they conduct at least substantially no heat.

With its side walls 40 the first plate forms a protective enclosure (cap) which minimalises the heat exchange between the first plate and the surroundings. If it is assumed that the heat exchange between the first plate and the surroundings is negligible, the temperature of the first plate will depend only on the heat exchange with the object 8 for measurement and the second plate. In this case the second plate has a heat exchange with the object, the first plate and the surroundings. The relevant heat flows are accordingly indicated in Fig. 5. Again it is assumed that the temperature of the first plate is the same throughout and that the temperature of the second plate is the same throughout. This assumption can readily be satisfied, for example, by making the first and second plates of aluminium or copper. It is also assumed that the thermal capacity of the first and second plates is much greater than that of the air between the object, the first plate and the second plate. It is not necessary for the thermal capacity of the first and second plates respectively to be small. If, as discussed in connection with Figs. 3 and 4, a Kalman filter is used, the inertia of the sensor unit can be so processed by the Kalman filter that this inertia is eliminated. In other words, if the sensor unit is required to measure a temperature jump, the temperature response of the plate temperatures will be exponential. The Kalman filter so processes these signals that there is again a temperature jump measured at the Kalman filter output. One example of this is shown in Fig. 7.

The above assumptions result in a sensor model according to equations 12 and 13, while $G_{0p1} = 0$ can be assumed in connection with the fact that it is assumed that the heat exchange between the first plate and the surroundings is negligible. On the basis of this assumption, the components of the system matrix A and of the amplification matrix K can be estimated once as described with reference to Fig. 3.

One advantage of the sensor unit according to Figs. 5 and 6 is that the object temperature can be reconstructed very accurately. This is caused particularly by the fact that the heat flow from the first plate to the surroundings is negligible. The complexity of the sensor model thus decreases, while the accuracy of the model increases. The temperature of the first plate in that case is of course determined solely by the heat flow Q_{vp1} from the object to the first plate and the heat flow Q_{p2p1} from the first plate to the second plate.

Another advantage of the embodiment according to Figs. 5 and 6 is that it is resistant to parameter variations such as air humidity. It is well known that air humidity has a considerable influence on the specific thermal conductivity of air. The numerical values of G_{xy} thus vary with the air humidity. However, it follows from formula 31 that the static temperature distribution does not depend on the absolute values of G_{xy}, but on the relationships therebetween. The filter 19 will continue to work well if all the G_{xy} values become, for example, 20% larger or smaller with a constant K.

The accuracy of the sensor unit can be improved further if the heat flow Q_{vp2} from the object of the second plate is small with respect to the heat flow Q_{vp1} from the object to the first plate, the heat flow Q_{p1p2} from the first plate to the second plate and the heat flow Q_{op2} from the second plate to the surroundings. In order to improve the accuracy of the sensor unit accordingly, an outer surface 44 of the first plate is preferably black. Of course this will involve the magnitude of the heat flow Q_{vp1} from the object to the first plate increasing. In addition, a black outer surface 44 makes the sensor unit less sensitive to soiling. Also, preferably, the inner surfaces of the first and second plates are reflecting. This can be achieved, for example, by making the first and second plates from reflecting aluminium.

The fact that the accuracy of the system increases as described above is also apparent from formulae 14, 15 and 16. If, for example, the heat flow between the surroundings and the first plate is negligible and if in addition the heat flow from the object to the second plate is small with respect to the remaining heat flows, then the coefficients G_{0p1} and G_{vp2} of the matrix G will be small with respect to the coefficients G_{vp1} and G_{op2}. Mathematically, this means that the angle between the specific vectors of the matrix G will approach 90°. In the extreme case, if the angle is equal to 90°, the equations 14 and 15 will be quite independent and the accuracy of the sensor system will be optimal with respect to the mechanical construction.

Preferably, the sensor unit is so dimensioned that in use the temperature difference $(T_v - T_{p1})$ between the object 8

and the first plate 4, the temperature difference (T_{p1} - T_{p2}) between the first and second plate 4, 14 and the temperature difference (T_{p2} - T_0) between the second plate 14 and the surroundings are approximately equal to one another. The said temperature differences are variables in the equations 12 and 13. Since these variables are now approximately all equal, the measuring error amplification in the Kalman filter 19 will be as small as possible.

In the example of Fig. 5, the distance d_1 between the first plate and the second plate is approximately equal to twice the distance d_2 between the object and the first plate. Other distances are feasible however. What is important is that the first plate is situated entirely within the space enclosed by the second plate. In that case the heat flow Q_{op1} will be very small. If the distance between the first plate and the second plate is small with respect to the distance between the first plate and the object, the influence of a change of the distance between the first plate and the object will be relatively small. This is important if the object consists of a heated rotating roller or heated endless belt. Preferably, the distance d_1 between the first plate and the second plate will be about 1 mm to 6 mm. The thickness of the first plate and the second plate is, for example, approximately 0.5 mm. If the plates are too thick, the temperature of the plates will not be the same throughout. If the plates are too thin, the sensor unit becomes too fragile and the thermal capacity of the plates may become too small with respect to the thermal capacity of the air between the object, the first plate and the second plate.

The invention is in no way limited to the above exemplified embodiments. For example, the control unit 12 may be provided with a first and second A/D conversion unit 46, 48 for sampling and digitising the first and second sensor signals. In that case the Kalman filter 19 is a digital filter, to which the digitised sensor signals are fed for further processing. The first and second A/D conversion units can, for example, be constructed with 8-bit resolution. In view of an expected measuring range of 20 to 120°C, the resolution will then be approximately 0.4°C. If, however, 12-bit A/D conversion units are used, the system noise referred to hereinbefore will decrease. The sampling time is preferably ten times less than the smallest response time to be measured by the sensor unit 2. In this example, Δt = 1.28 sec can be chosen. The Kalman filter according to Fig. 3, which is thus suitable for processing analog signals, can be of digital construction in manner known per se, as will be explained summarily hereinafter. The following can be derived from formula 25:

$$d\bar{x} = A\bar{x}(t) \cdot dt + \bar{w}(t) \cdot dt \tag{38}$$

If $\bar{x}_i$ is the ith sampled digitised value of $\bar{x}$, where Δt is equal to the sampling time, then the following can be derived from equation 38:

$$\bar{x}_{i+1} - \bar{x}_i = A\bar{x}_i \Delta t + \bar{w}_i \Delta t \tag{39}$$

From equation 39 it simply follows that:

$$\bar{x}_{i+1} = (A \Delta t + I) x_i + \bar{w}_i \Delta t \tag{40}$$

Equation 40 can be rewritten as follows:

$$\bar{x}_{i+1} = A'\bar{x}_i + \bar{w}'_i \tag{41}$$

Similarly equations 27, 30, 32 and 35 are equivalent to the following equations, which can be used for a digital Kalman filter:

$$\bar{Y}_i = \begin{pmatrix} T_{p1_i} \\ T_{p2_i} \end{pmatrix} + \bar{v}_i = C\bar{x}_i + \bar{v}_i \tag{42}$$

$$J = \sum_{i=0}^{n} (\bar{x}_{mi} - x_{Mi})^2 = minimal \tag{43}$$

$$J' = \sum_{i=0}^{n} (\bar{x}_{mi} - \hat{x}_i)^2 = minimal \tag{44}$$

$$\hat{\bar{x}}_{i+1} = (A' - KC) \bar{x}_i + K \bar{y}_i \tag{45}$$

If the sensor unit is constructed in accordance with Fig. 5, and if it is also assumed that the heat flow from the first plate to the surroundings is equal to zero, then it is a simple matter to derive the following applicable to the matrix A':

$$A' = \left(\begin{pmatrix} \dfrac{G_{vp1}+G_{p1p2}}{C_{p1}} & \dfrac{-G_{p1p2}}{C_{p1}} & \dfrac{-G_{vp1}}{C_{p1}} & 0 \\[2mm] \dfrac{-G_{p1p2}}{C_{p2}} & \dfrac{-G_{0p2}+G_{vp2}+G_{p1p2}}{C_{p2}} & \dfrac{-G_{vp2}}{C_{p2}} & \dfrac{+G_{0p2}}{C_{p2}} \\[2mm] 0 & 0 & 0 & 0 \\[2mm] 0 & 0 & 0 & 0 \end{pmatrix} \Delta t + \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \right) \tag{46}$$

Finally, the digital version of the Kalman filter is shown in brackets in Fig. 3.

For the sake of completeness it should be noted that the term Kalman filter in this context also includes an extended Kalman filter and an adaptive Kalman filter. Also, other choices are possible for a filter design. For example three state variables can be taken as a basis instead of four. The three state variables of x could, for $\bar{x}$ example, be T_v, T_{p1} and T_{p2}. The fact that heat flows from and to the surroundings are completely ignored in such a model

$$(\dot{\bar{x}} = A\bar{x})$$

can possibly be expressed in somewhat larger values

$$\bar{w}(\dot{\bar{x}} = A\bar{x}+\bar{w}) \cdot$$

Non-linear filter algorithms such as are usual in robotics can also be implemented.

These variants are all considered as coming within the scope of the invention.

Claims

1. A temperature measuring system for the contactless determination of the object temperature (T_v) of at least a part of an object, provided with a sensor unit which is to be placed near the object and which comprises a first metal plate on which a first temperature-sensitive sensor is disposed to produce first sensor signals which represent the temperature (T_{p1}) of the first plate and a control unit which processes the first sensor signals for determining the object temperature (T_v),

   characterised in that the sensor unit is also provided with a second metal plate spaced from the first plate and having a second temperature-sensitive sensor disposed thereon to produce second sensor signals representing the temperature (T_{p2}) of the second plate, the control unit processing the first and second sensor signals in combination with one another to determine the object temperature (T_v).

2. A temperature measuring system according to claim 1, characterised in that the second plate is so positioned with respect to the first plate that if in respectively stable states ratios (T_0/T_v) between, on the one hand, an ambient tem-

perature (T_0) of the sensor unit and, on the other hand, the temperature (T_V) of the object differ from one another the associated ratios ((T_{p1}/T_{p2}) between, on the one hand, the temperature (T_{p1}) of the first plate and, on the other hand, the temperature (T_{p2}) of the second plate also differ from one another.

5   3.   A temperature measuring system according to claim 1 or 2, characterised in that the first plate and the second plate each comprise an inner surface and an outer surface situated on either side of the plate, the inner surfaces of the first plate and the second plates facing one another.

4.   A temperature measuring system according to claim 3, characterised in that the first plate and the second plate are
10   at least substantially flat and at least substantially parallel to one another.

5.   A temperature measuring system according to claim 3 or 4, characterised in that the second plate is also provided with side walls which extend from the inner surface of the second plate in the direction of the first plate, the first plate being situated within a space enclosed by the side walls of the second plate and the first plate being situated,
15   in use, between the second plate and the object.

6.   A temperature measuring system according to any one of the preceding claims 3 to 5, characterised in that the inner surfaces of the first plate and the second plate are each reflecting.

20   7.   A temperature measuring system according to claim 6, characterised in that at least one of the inner surfaces of the first plate and the second plate is made from reflecting aluminum.

8.   A temperature measuring system according to any one of the preceding claims 3 to 7, characterised in that the outer surface of the first plate is black.
25
9.   A temperature measuring system according to any one of the preceding claims, characterised in that the first plate and the second plate are interconnected by connecting means which have at least substantially no thermal conductivity.

30   10. A temperature measuring system according to claim 5, characterised in that the distance between the first plate and the second plate is so dimensioned that in use the temperature difference (T_V-T_{p1}) between the object and the first plate, the temperature difference (T_{p1}-T_{p2}) between the first plate and the second plate and the temperature difference (T_{p2}-T_0) between the second plate and the surroundings are at least substantially equal to one another.

35   11. A temperature measuring system according to claim 5 or 10, characterised in that the distance between the first plate and the second plate is so dimensioned that in use the distance between the first plate and the second plate is approximately equal to twice the distance between the first plate and the object.

12. A temperature measuring system according to claim 4, characterised in that the distance between the first plate
40   and the second plate is 1 mm to 6 mm.

13. A temperature measuring system according to claim 4 or 12, characterised in that the area of the first plate and the second plate respectively is 2 cm^2 to 20 cm^2.

45   14. A temperature measuring system according to any one of the preceding claims, characterised in that the first temperature sensor is provided with a first temperature-sensitive resistor.

15. A temperature measuring system according to claim 14, characterised in that the first temperature-sensitive resistor consists of an NTC.
50
16. A temperature measuring system according to any one of the preceding claims, characterised in that the second temperature sensor is provided with a second temperature-sensitive resistor.

17. A temperature measuring system according to claim 16, characterised in that the second temperature-sensitive
55   resistor consists of an NTC.

18. A temperature measuring system according to any one of the preceding claims, characterised in that the control unit comprises a filter for determining the object temperature (T_V) on the basis of the first and second sensor signals.

19. A temperature measuring system according to claim 18, characterised in that the filter consists of a Kalman filter.

20. A temperature measuring system according to claim 18 or 19, characterised in that the filter is dimensioned on the basis of a model having at least three state variables which are respectively formed by the temperature (T_{p1}) of the first plate, the temperature (T_{p2}) of the second plate and the object temperature (T_v) and with measured variables formed by the temperature (T_{p1}) of the first plate and the temperature (T_{p2}) of the second plate.

21. A temperature measuring system according to claim 20, characterised in that the filter is dimensioned in manner known per se on the basis of a model having state variables formed by the temperature (T_{p1}) of the first plate, the temperature (T_{p2}) of the second plate, the object temperature (T_v) and the ambient temperature (T_0) of the sensor unit and with measured variables which are formed by the temperature (T_{p1}) of the first plate and the temperature (T_{p2}) of the second plate.

22. A temperature measuring system according to claim 21, characterised in that the model is based on the following differential equations:

$$C_{p2} \frac{dT_{p2}}{dt} = G_{vp2}(T_v - T_{p2}) + G_{0p2}(T_0 - T_{p2}) = G_{p1p2}(T_{p1} - T_{p2})$$

$$C_{p1} \frac{dT_{p1}}{dt} = G_{vp1}(T_v - T_{p1}) + G_{0p1}(T_0 - T_{p1}) = G_{p1p2}(T_{p2} - T_{p1})$$

where

C_{p1} is the thermal capacity of the first plate;
C_{p2} is the thermal capacity of the second plate;
G_{vp1} is the heat transfer coefficient between the object and the first plate;
G_{vp2} is the heat transfer coefficient between the object and the second plate;
G_{0p1} is the heat transfer coefficient between the surroundings of the sensor unit and the first plate;
G_{0p2} is the heat transfer coefficient between the surroundings of the sensor unit and the second plate;
G_{p1p2} is the heat transfer coefficient between the first plate and the second plate;
T_v is the object temperature requiring to be determined;
T_0 is the ambient temperature for the sensor unit;
T_{p1} is the temperature of the first plate; and
$_{p2}$ is the temperature of the second plate.

23. A temperature measuring system according to claims 5 and 22, characterised in that in the model the heat transfer coefficient G_{op1} from the surroundings to the first plate is assumed to be zero.

24. A temperature measuring system according to any one of the preceding claims 18 to 23, characterised in that the control unit comprises an A/D conversion unit for sampling and digitising the sensor signals; and in that the filter is a digital filter to which the digitised sensor signals are fed.

25. A sensor unit for use in a temperature measuring system according to any one of the preceding claims.

26. An image reproduction machine provided with a temperature measuring system according to any one of the preceding claims 1 to 24.
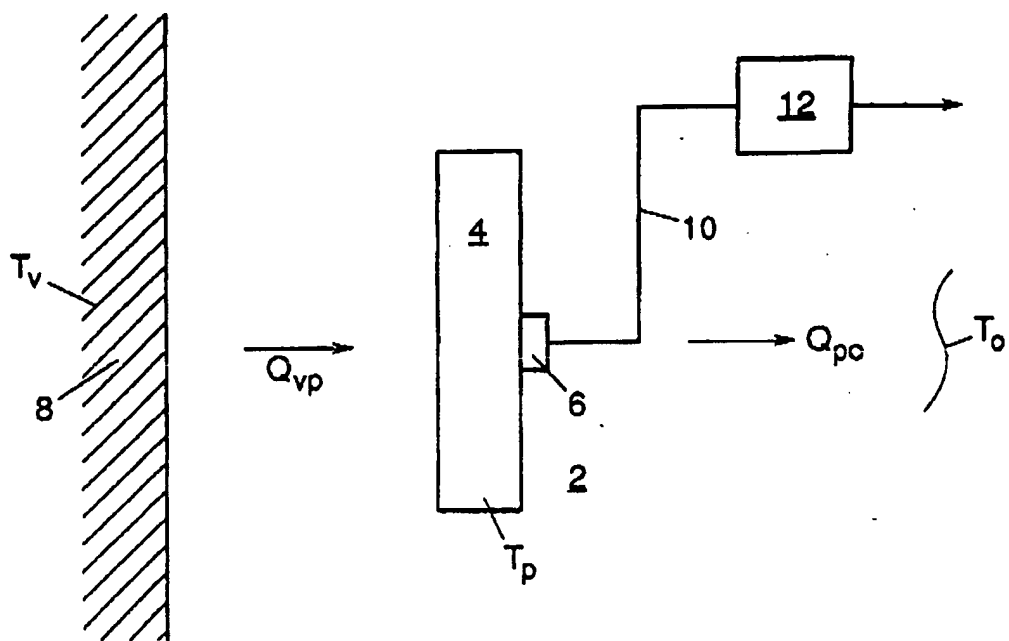
T_v

8

Q_{vp}

4

10

12

6

Q_{po}

T_o

2

T_p

FIG. 1

12

$\hat{T}_v(t)$

10

T_v

Q_{vp_1}

4

Q_{p_1o}
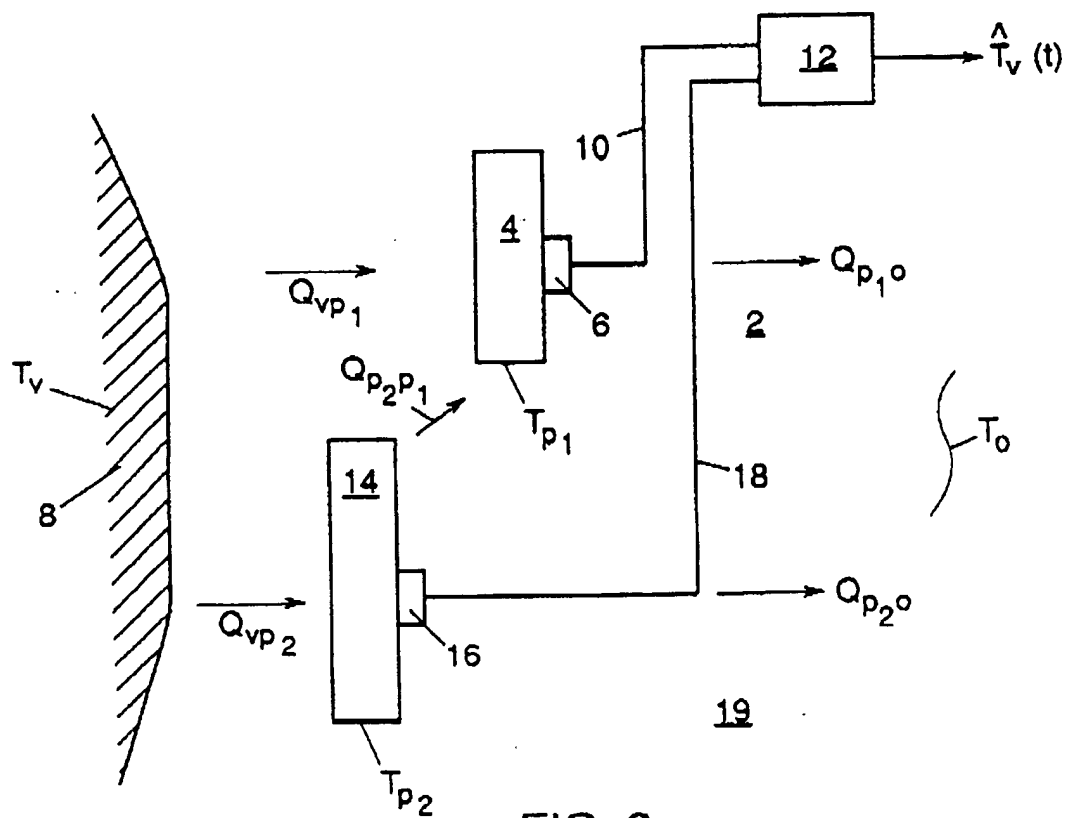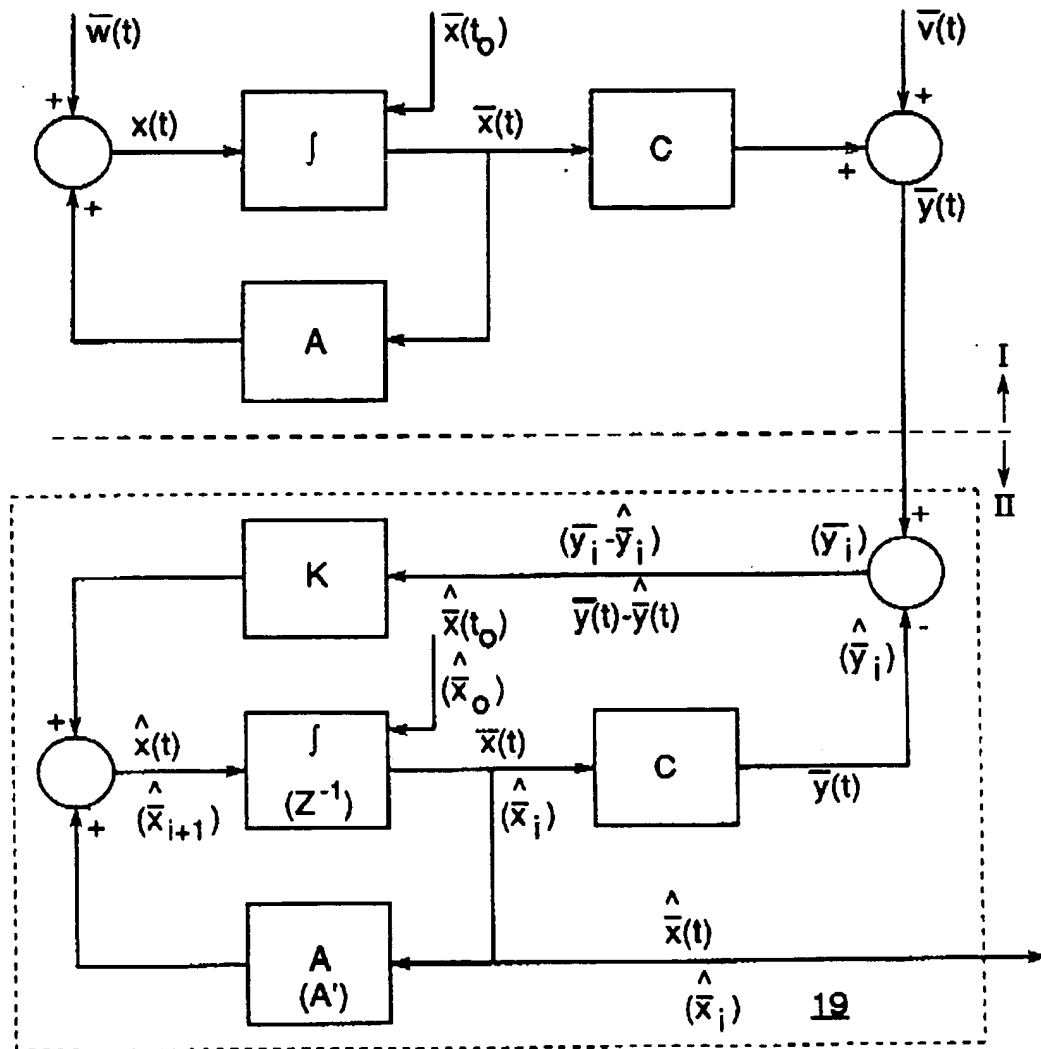
8

$Q_{p_2p_1}$

6

2

T_{p_1}

T_o

14

18

Q_{vp_2}
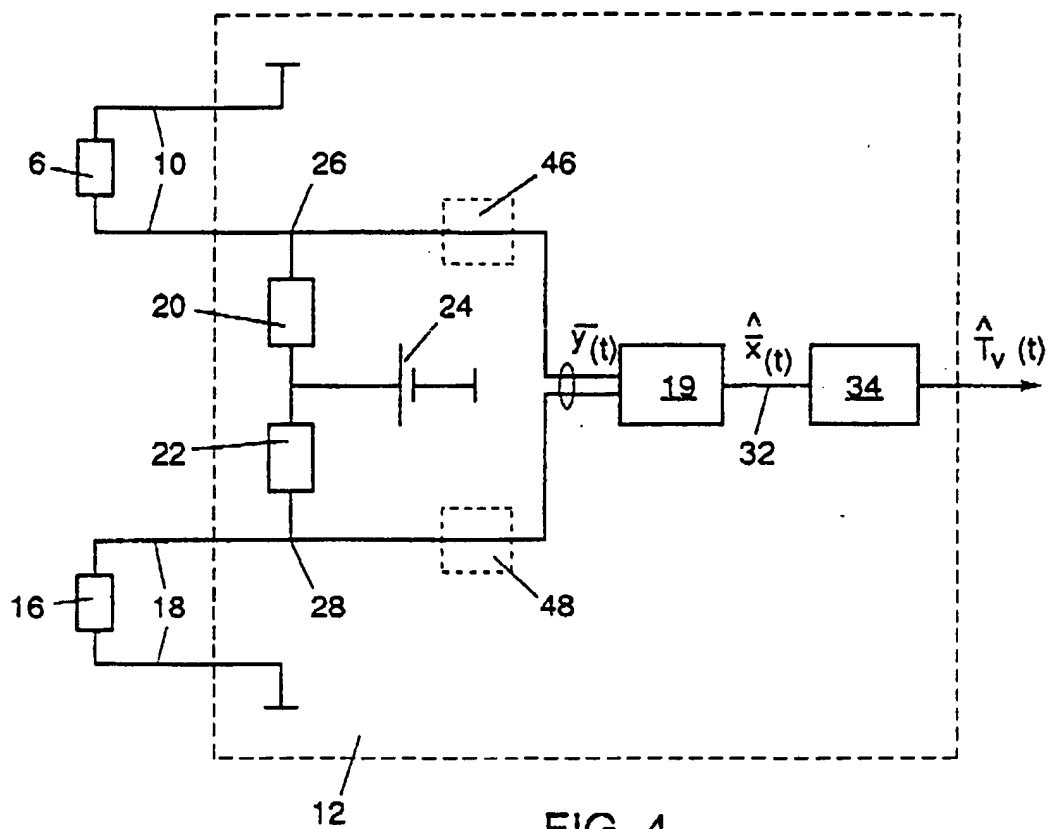
16

Q_{p_2o}

19

T_{p_2}
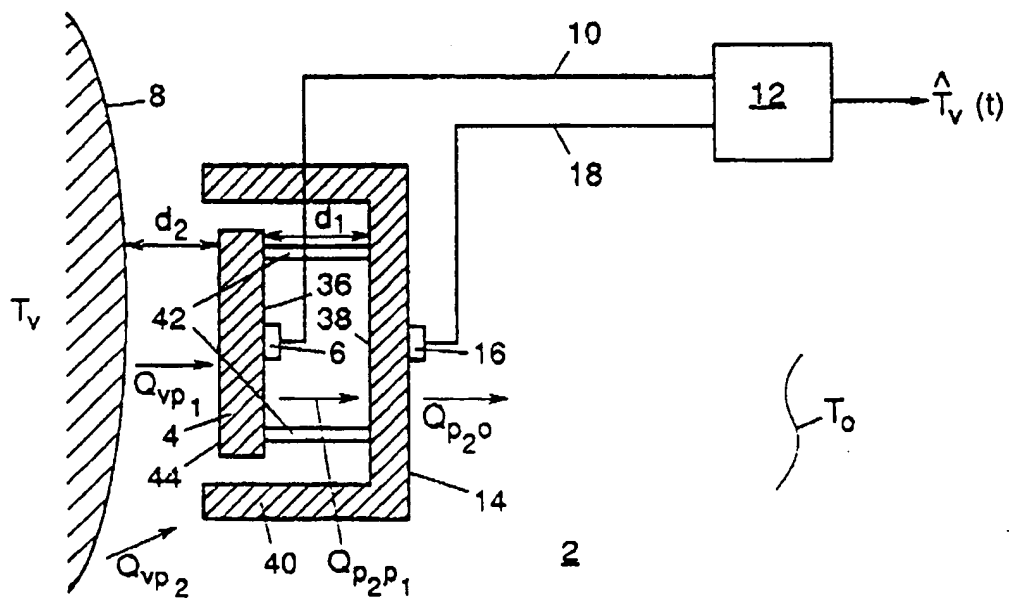
FIG. 2

FIG. 3
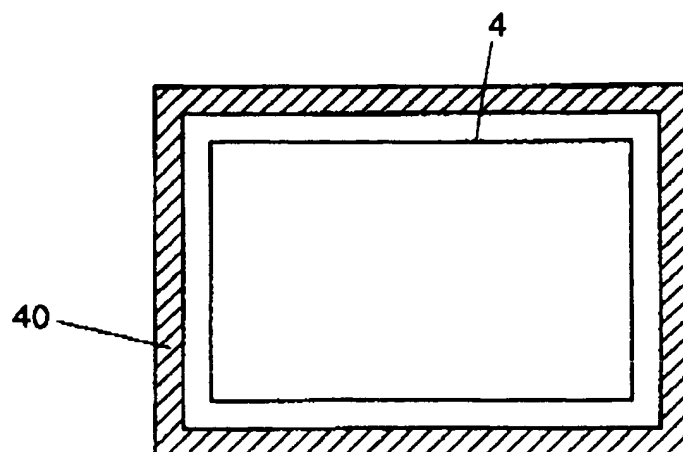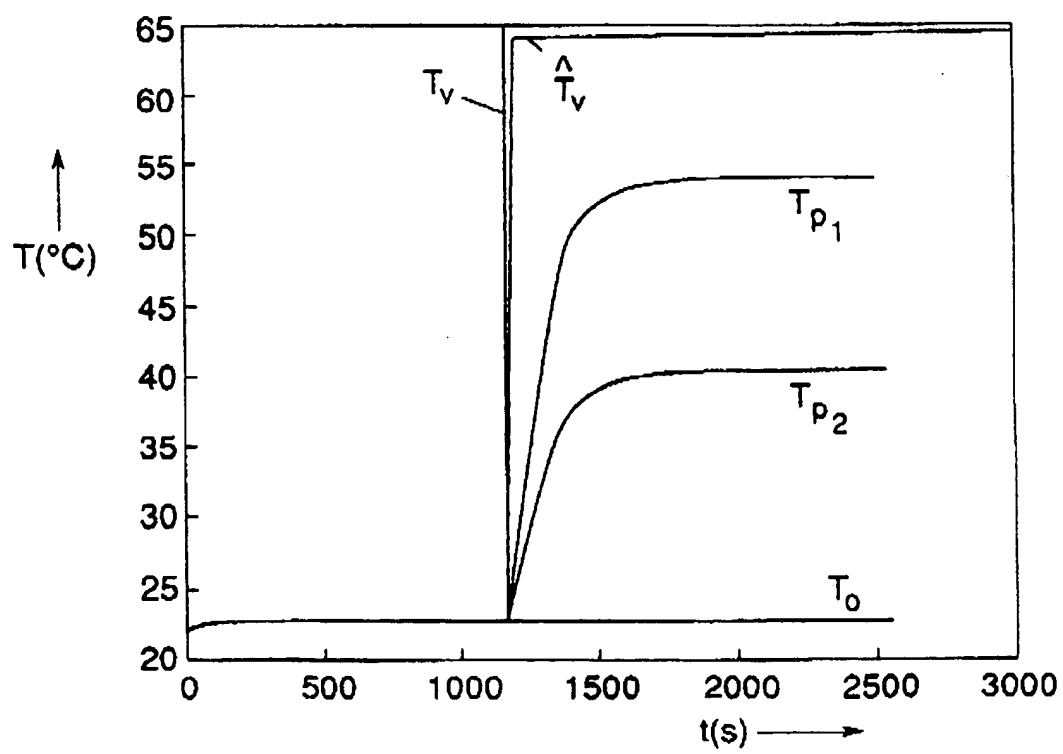
FIG. 4

FIG. 5

FIG. 6

FIG. 7

European Patent Office

EUROPEAN SEARCH REPORT

Application Number

EP 96 20 1915

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
A	LA TECHNIQUE MODERNE, vol. 55, no. 7, pages 313-313, XP002016500 ANONYMOUS: "L'EXPOSITION DE L'INSTITUE OF PHYSICS ET DE LA PHYSICAL SOCIETY" * column 2 * ---	1,3-5	G01K13/04 G03G15/20
A	NL-C-73 597 (WINGFOOT CORP.) 15 June 1953 * the whole document * ---	1	
D,A	US-A-5 287 155 (ARAI E.A.) 15 February 1994 * the whole document * ---	1,26	
A	WO-A-81 00452 (LUNDBACK) 19 February 1981 * abstract * -----	18	
			TECHNICAL FIELDS SEARCHED (Int.Cl.6)
			G01K G03G

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	22 October 1996	Ramboer, P

CATEGORY OF CITED DOCUMENTS

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